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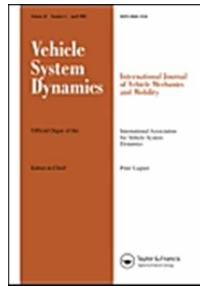
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A Finite Element based approach to characterising FTire model for extended range of operation conditions

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Abstract: In order to accurately predict vehicle dynamic responses when traversing high obstacles or large bumps, appropriate tire models need to be developed and characterised. Tire models used in vehicle ride and durability are usually characterised by experimental tests on the tire. However, limitations in rig design and operating conditions restrict the range of test conditions under which the tyre can be tested, hence characterisation of the tire behaviour during extreme manoeuvres may not be possible using physical tests. In this study, a combination of experimental tests and Finite Element (FE) modelling is used in deriving Flexible Ring Tire (FTire) Models appropriate for different levels of tire/road interaction severity. It is shown that FE modelling can be used to accurately characterise the behaviour of a tire where limitations in experimental facilities prevent tire characterisation using the required level of input severity in physical tests. Multi-Body Simulation is used to demonstrate that the FTire model derived using extended range of obstacles produces more accurate transient dynamic response when traversing low and high road obstacles.

Key words: Finite Element, FTire, multi-body dynamics, high obstacle, extended condition

1. Introduction

Since tires on a passenger vehicle are vital components connecting the road and the vehicle, tire model development is very important for prediction of vehicle dynamic response to road inputs. For a travelling vehicle, the tires transmit forces generated on the road surface and, therefore, the forces generated when a tire impacts the road surface need to be accurately predicted. And also, tire models used in vehicle dynamics simulation for CAE durability and ride comfort assessment need to be capable of predicting the non-linear deformation and enveloping characteristics which occur when traversing large road obstacles.

Recently, some empirical and semi-empirical tire models were developed to characterise tire enveloping behaviour when rolling over obstacles. Guan and Fan [1, 2] established a semi-empirical tire model derived from experimental modal parameters below 350Hz extracted from the radial and tangential responses under radial and tangential excitation. With consideration of the nonlinear stiffness of tire sidewall, a quantitative in-plane rolling tire model was developed to investigate tire dynamic responses and enveloping properties when the tire rolls over different cleats with different values of inflation pressure and wheel load in the time domain and frequency domain respectively. The SWIFT model [3, 4]

developed by Delft University of Technology in cooperation with the TNO Automotive is also capable of predicting tire enveloping properties in the condition of relatively short wavelength (0.1-0.2m). However, only modestly high road obstacles (no higher than 20 mm) were applied to these models, which may lead to inaccuracy for prediction of tire transient dynamic responses for more severe conditions.

FTire™, in the form of a reduced FE model is one of the models of choice for this purpose in the industry. FTire model is composed of the structural model and the tread/road contact model [5-10]. The structural model is used to describe the structural damping, stiffness and inertia characteristics of the tire, while the tread/road contact model is developed to determine the contact pressure and friction distribution on the contact patch. Nowadays, FTire model is a widely used commercial model in many industries because of its benefits in application, such as ease of implementation with multiple instances, fully nonlinear property, and good accuracy when passing single obstacles like cleats and potholes. Riepl et al. [11] applied FTire model for the automotive development at MAGNA STEYR Fahrzeugtechnik in the multi-body application tasks such as suspension analysis, vehicle handling, and ride comfort simulation. After this, Riepl and his colleagues [12] carried out a virtual rough road ride simulation with FTire and RMOD-K, and the two tire models were compared to six ride measurements. In terms of the calculation time efficiency, FTire performed better than RMOD-K. Haga [13] made an evaluation of tire models for durability loads prediction using a suspension on a drum environment. FTire was one of the two tire models used for vehicle dynamics simulation. The vertical and longitudinal responses in the time domain were obtained using multibody simulations (MBSs) with FTire and LMS CDtire. With the application of tire models, he concluded that MBSs using the tire model FTire is suitable for real world applications for durability performance. However, the input parameters of the FTire model have not been given in Haga's study.

In order to characterise the tire behaviour for FTire model, experimental tests on the tire need to be carried out to acquire important data, such as static stiffness and dynamic responses data. Dorfi [14, 15] carried out simple stiffness and vibration measurements to characterize the tire properties. Vibration modes of the tires were obtained with simple vibration testing of the inflated tire on a fixed hub. The tire force responses for 10mm semi-circle and 10mm trapezoidal cleats were obtained using the derived FTire. Dorfi's study showed satisfactory predictions using FTire model, but many measurements were carried out and many tires were used in the tests in order to accurately characterize the tire properties.

An accurate FTire model for tire and vehicle dynamics analysis needs lots of test data for derivation of FTire parameters. A variety of measurements (static and dynamic tests) need to be carried out to characterise tire behaviour. Particularly, for the investigation of tire performance in severe conditions such as high bump and large obstacle, the transient dynamic responses need to be achieved for derivation of more accurate FTire model. This means some extra transient dynamic tests need to be carried out. However, considering the limitations of laboratory facilities and safety issues, measurements are very difficult to realise for the tire traversing obstacles beyond 25 mm height.

In this case, a validated FE tire model was chosen to predict the dynamic responses of the rolling tire at very severe conditions (i.e. high obstacles). Because of the accuracy and popularity of FE packages, they have been widely used for investigation of tire dynamic performance in the past decades. Olatunbosun and Burke [16] developed a time domain rotational tire model for the study of the dynamic behaviour of a rolling tire traversing a cleat using FE method, using the MSC/NASTRAN commercial FE code in their simulations. Kao et al. [17, 18] predicted tire dynamic responses for tire rolling over an attached semi-circular cleat using explicit FE program. Transient dynamics of a tire rolling over small obstacles have also been studied by Cho et al. [19] using a 3D patterned tire model, and detailed tread blocks was used in the model to accurately model the tire-cleat impact process. However, only small size obstacles have been used in these studies, whereas the high frequency dynamic responses for large obstacles are ignored.

In this study, FE numerical simulations and experimental validations including static analysis, cornering property analysis, and transient dynamic analysis for the high obstacles are carried out. The validated FE tire model is then used for predicting the dynamic performance for higher obstacles, which is considered as severe condition. The predicted responses for the severe conditions together with the previous results are finally used to derive an extended FTire model.

2. FE model description and Experimental validation

2.1 FE tire model description

In this study, a 235/60R18 tire is adopted for analysis. The two-dimensional (2D) tire model is established firstly and the three-dimensional (3D) tire model was then created by simply revolving the 2D model, both the 2D model and the generated 3D model are illustrated in Figure 1. The hybrid axisymmetric elements with twist degree of freedom (CGAX4H and CGAX3H) were used to define the rubber components in the 2D model, while the reinforcements were represented by linear axisymmetric surface elements with 2 nodes (SFMGAX1), which are embedded in rubber components. After the revolving of the 2D model, the 2D axisymmetric elements (CGAX4H and CGAX3H) were transformed into 3D solid elements (C3D8H and C3D6H), and the SFMGAX1 elements were transformed to the 4-node quadrilateral surface elements (SFM3D4R). In order to carry out explicit dynamic analysis in time domain for the tire rolling over cleats, the tire model with uniform meshes was chosen to simulate tire rolling. Note that the uniform 3D FE model is composed of 13802 finite elements and 17502 nodes. The wheel centre was fixed by constraining four degrees of freedom of the tire cross-section (two translational degrees and two rotational degrees). In order to constrain the bead nodes of the tire model, a rigid body between rim node and the tire-rim assembly nodes was defined using the tie function in ABAQUS™. In this way, it is more convenient to apply boundary conditions on the rim reference node to stabilize the tire-rim interface. It is also pertinent to note that the road was defined as an analytical rigid surface, and the cleats can be directly fixed on the surface for transient dynamic analysis.

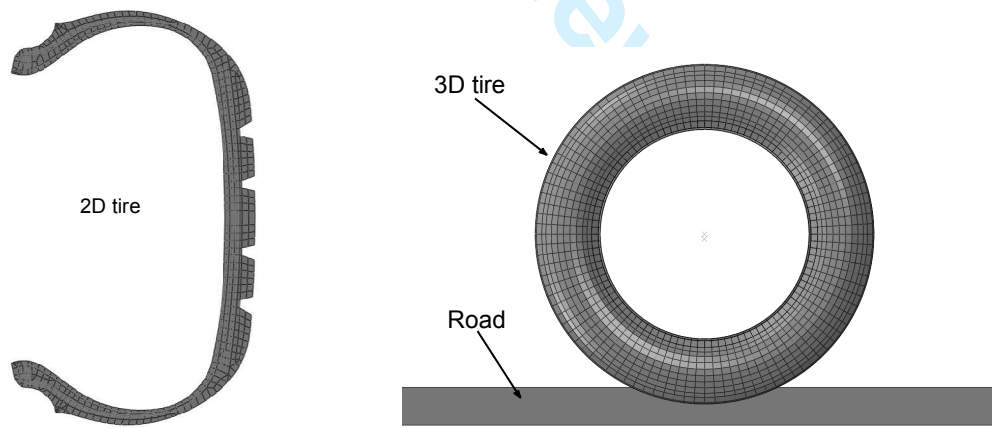


Figure 1. 2D FE tire model and the transferred 3D tire model

With regard to the definition of the material properties of the tire, the specimens of tire rubber and reinforcement components were extracted from the tire product. The material properties of the tire components defined in ABAQUS™ were obtained using a combination of curve fitting of experimental test results and numerical modelling in finite element simulation, and the reader can refer to literature [20, 21] for detailed description of this method. The hyperelastic property of rubber components of the tire was modelled using the Yeoh model [22], the strain energy function is expressed by

$$U = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 + \frac{1}{D_1}(J^{el} - 1)^2 + \frac{1}{D_2}(J^{el} - 1)^4 + \frac{1}{D_3}(J^{el} - 1)^6 \quad (1)$$

where U represents the strain energy density; C_{10} and D_i are material constants to be determined by testing and test data fitting in ABAQUSTM, which describe the shear behaviour and material compressibility separately; J^{el} is the elastic volume ratio, while I_1 is the first deviatoric strain invariant.

The viscoelastic material property response is defined in the time domain in ABAQUSTM by a Prony series expansion of the dimensionless relaxation modulus presented as follows [23]

$$g_R(t) = 1 - \sum_{i=1}^N \overline{g}_i^p (1 - e^{-t/\tau_i^G}) \quad (2)$$

where N , \overline{g}_i^p and τ_i^G represent material constants to be determined by modelling the physical test data in ABAQUSTM. In terms of reinforcements, a linear elastic material property was assumed, and the elastic material modulus and Poisson's ratio were used to characterise the behaviour of the reinforcements [24]. The estimated constants of the hyperelastic and viscoelastic properties for all the rubber components can be found in Table 1 and Table 2.

Table 1 Hyperelastic property constants for rubber materials [21]

Rubber Material	Yeoh strain energy potentials constants		
Component	C10	C20	C30
Tread	0.73	-0.18	7.96E-02
Sidewall	0.71	-0.28	0.13
Apex	1.28	-1.25	1.20

Table 2 Viscoelastic property constants for rubber materials [21]

Rubber Material	Prony series parameters					
Component	g_1	k_1	τ_1	g_2	k_2	τ_2
Tread	0.08	0	2.39E-5	0.07	0	142.83
Sidewall	0.10	0	2.07E-6	0.07	0	146.11
Apex	0.15	0	5.76	0.08	0	220.41

2.2 Validation of the FE tire model

In order to characterise the tire behaviour and derive FTire parameters, some necessary experiments and simulations need to be carried out for data collection. In this study, the static, steady-state and transient dynamic behaviours are characterised using the FE model, and the corresponding experiments are conducted for FE model validation.

2.2.1 Static properties validation

Tire radial stiffness is one of the important static parameters of a tire, and can be affected by many factors including inflation pressure, tire structure and tire material etc [25-28]. In this study, the tire radial stiffness at a normal inflation pressure was validated with the static measurement, which was taken from the same tire used to conduct numerical simulations, as shown in Figure 2.

The size and shape of the footprint of a tire as well as the pressure distribution within the footprint are significant factors for tire properties, especially ride performance and handling properties of a vehicle. The footprint of the tire was extracted using a sheet of white paper attached on the test rig. Figure 3 illustrates the comparison between the measured and predicted tire footprints under the same conditions (200kPa inflation pressure and 3000N radial load). It can be found that satisfactory results including the stiffness and the shape of contact patch are obtained through the validation of the static behaviour. Figure 4 proposed the validation of the footprint areas for different inflation pressures and satisfactory results are obtained.

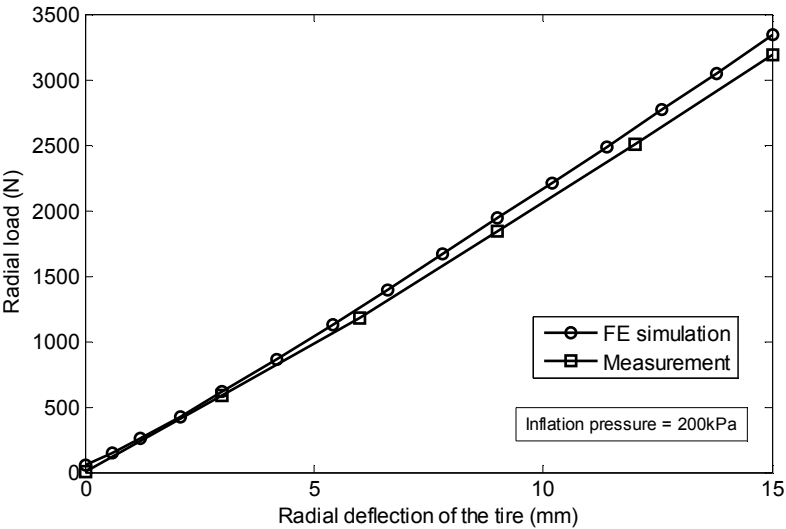


Figure 2. Tire radial stiffness validation

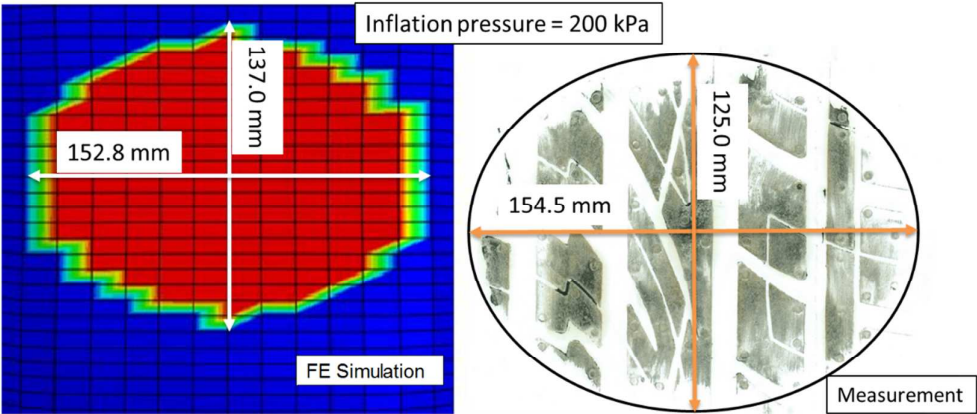


Figure 3. Tire/road contact footprint validation

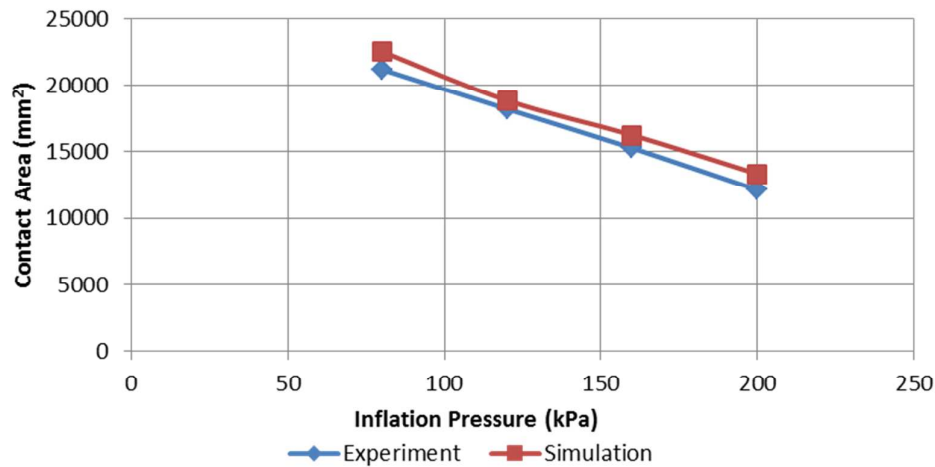


Figure 4 Footprint area for different inflation pressures

2.2.2 Cornering properties validation

The cornering property of a tire has a significant effect on the directional control and handling stability of the vehicle [29-32]. Cornering forces are predicted for the slip angle ranging from 0 degree to 7 degrees under the following conditions: 200 kPa inflation pressure, 2000/3000 N radial load. It is noted that due to the equipment limitations and safety issue, the rolling velocity was only set as 10 km/h. The simulation results of cornering forces predicted using the tire model and the corresponding experiment results are compared with each other, as shown in Figure 5. Particularly, in order to reflect reasonable tire/road contact situation, the frictional coefficient applied in the tire, with relation to the cornering test, is set as 1.0 [31]. It can be seen from the comparison that the predicted cornering stiffness agrees well with the measurement data for both 2000N and 3000N radial loads.

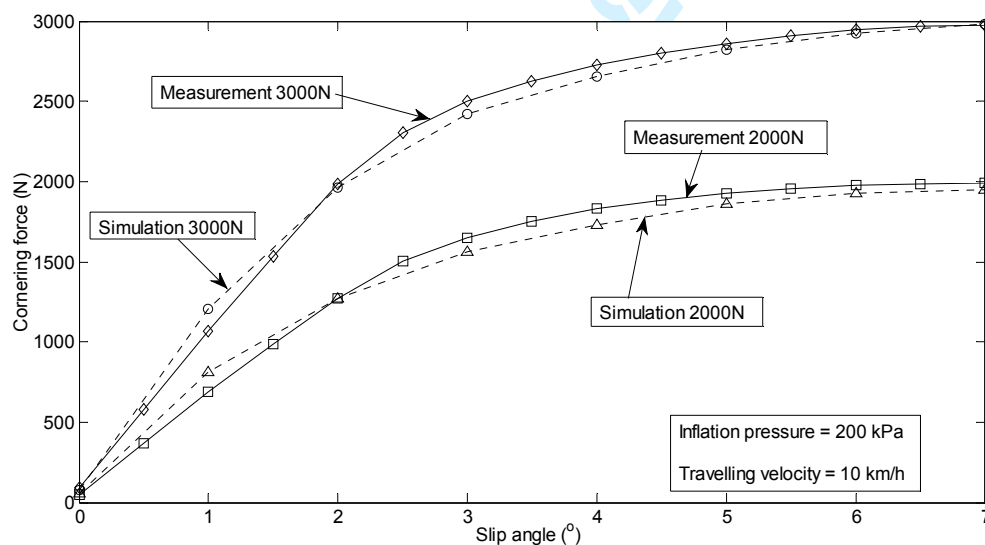


Figure 5. Cornering stiffness validation for different radial loads

2.2.3 Transient dynamic properties validation

Tire transient dynamic performance is analysed by predicting the tire dynamic responses when rolling over a cleat, and actually the uneven road is formed by a series of obstacles in practice [32]. The

rectangular cleats with different heights (10 mm, 20 mm, and 25 mm) were designed and defined as the road obstacles. Figure 6 shows the process of the tire rolling over an obstacle in the time domain. The drum used in the experiment has a diameter of 2.4m. This provides a near enough flat surface for the static and steady-state analysis. Error in contact area is estimated to be less than 3%. Based on this, the flat surface was applied to defined as road surface. The longitudinal and vertical forces for this process are predicted for these three obstacles, and the dynamic responses for simulations and measurements at 30 km/h are shown in Figure 6. It is obvious to see that the predicted tire dynamic responses agree well with the measurements for all the three obstacles. Particularly, the measured and predicted peak values of the vertical force for 10 mm high obstacle are 5106 N and 4803 N, and the corresponding longitudinal force peak values are 3578 N and 3040 N. For the 20 mm high obstacle, the peak values of vertical force for the measurement and simulation are 6182 N and 6745 N, and the longitudinal peak forces are 6912 N and 5341 N. When the tire rolls over the 25 mm high obstacle, the peak vertical forces for the measurement and simulation are 7619 N and 7523 N, and the corresponding longitudinal peak forces are 8465 N and 7816 N. It can be seen that both the vertical and longitudinal peak values have satisfactory differences for all the three cases.

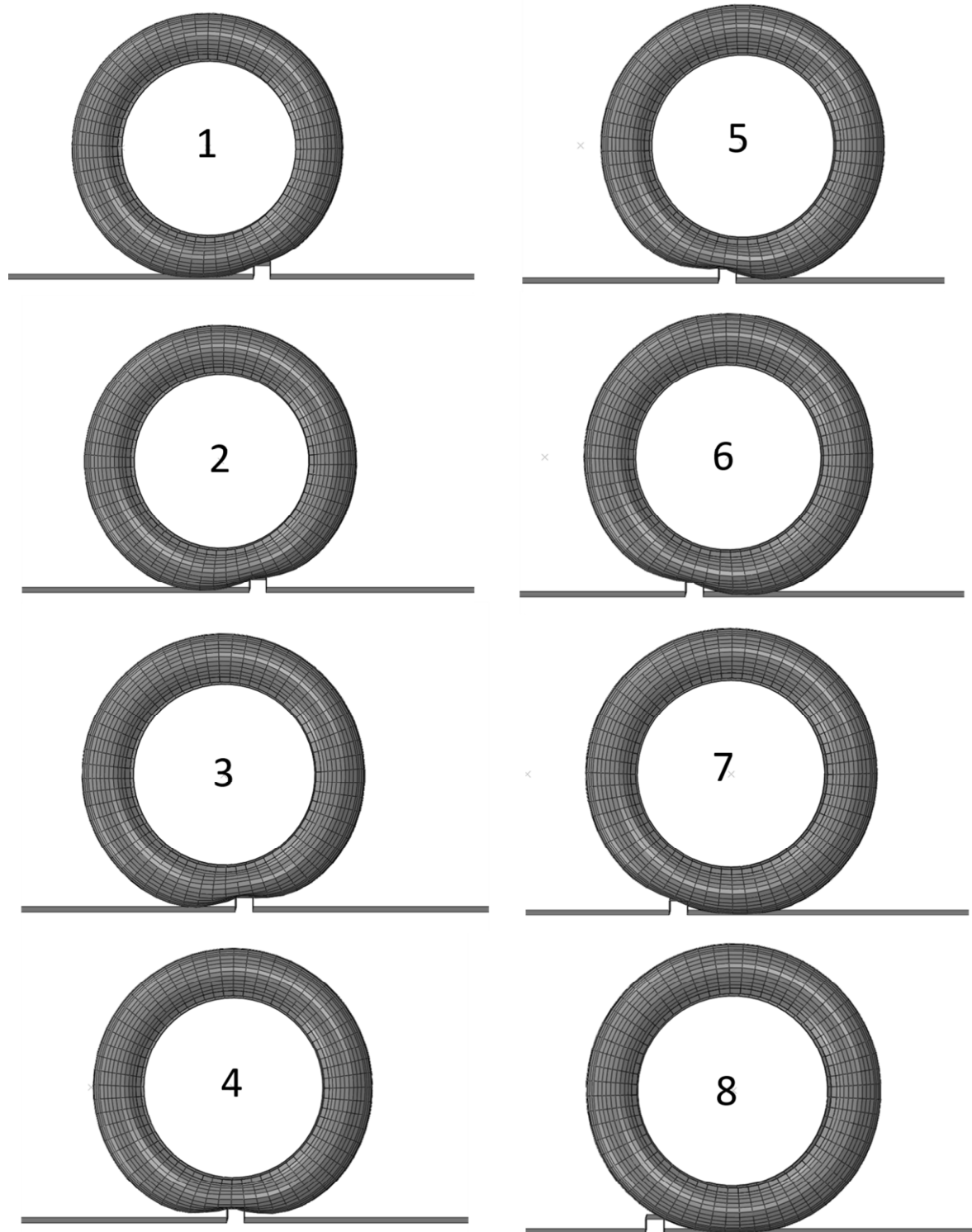


Figure 6. The process of the tire rolling over a cleat in simulation

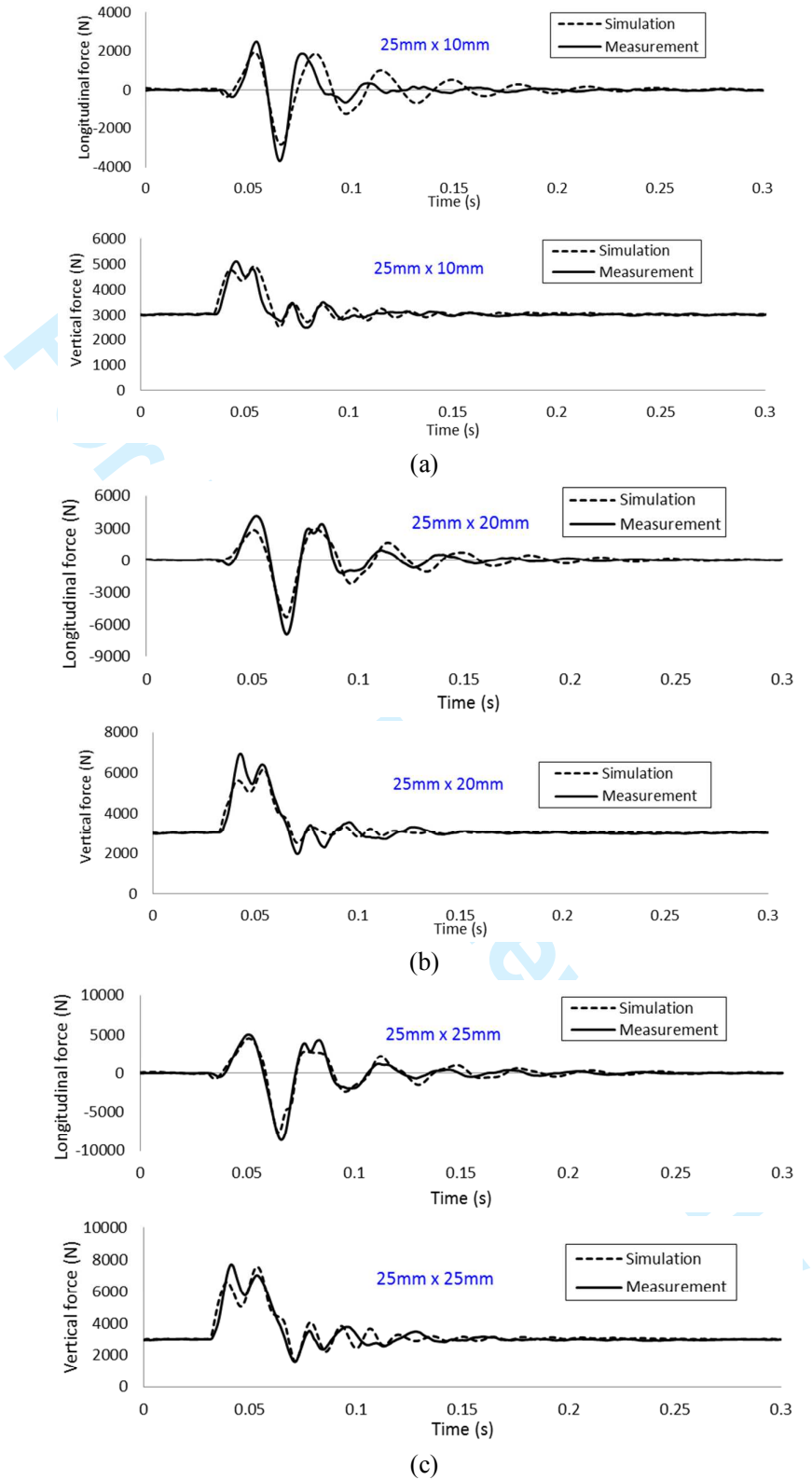


Figure 7. Spindle responses for tire rolling velocity of 30 km/h (a) longitudinal and vertical responses for obstacle 25 mm × 10mm, (b) longitudinal and vertical responses for obstacle 25 mm × 20 mm, (c) longitudinal and vertical responses for obstacle 25 mm × 25 mm. The inflation pressure was 200 kPa and the vertical pre-load was set as 3000 N.

3. Extended FTire derivation using measurement and simulation data

3.1 Procedure of generating FTire parameters

The general parameters of FTire that need to be derived are composed of the basic geometric data, tread stiffness, sidewall stiffness, damping properties, belt properties, friction properties etc. With the existing tire static and dynamic data, FTire parameters can be generated using FTire/fit, which is a parameter identification and validation toolbox for FTire. The following tire static and dynamic data from simulations or measurements are taken as input data in FTire/fit tool:

- Static tire properties (cross-section shape, static stiffness)
- Footprint shapes
- tire properties in steady-state rolling conditions (cornering stiffness)
- time-domain spindle responses for cleat tests or simulations (radial forces, longitudinal forces)

3.2 FTire models derivation using different input data

To identify the accuracy of generated FTire models using FE model, different input data are chosen for derivation of FTire parameters.

In this study, three kinds of FTire models are obtained with different input data described as follows:

FTire#a: FTire derived by Measurement data

- Footprint shapes
- Static and steady-state case
- In-plane cleat test data (25 mm × 10 mm, 25 mm × 20 mm, 25 mm × 25 mm)

FTire#b: FTire derived by FE simulation data for normal road obstacles

- Footprint shapes
- Static and steady-state case
- In-plane cleat simulation data (25 mm × 10 mm, 25 mm × 20 mm, 25 mm × 25 mm)

FTire#c: FTire derived by FE simulation data including higher road obstacles

- Footprint shapes
- Static and steady-state case
- In-plane cleat simulation data (25 mm × 10 mm, 25 mm × 20 mm, 25 mm × 25 mm, 25 mm × 30 mm, 25 mm × 40 mm)

With the help of FTire/tools and FTire model theory [7], the three FTire models were derived. Due to the differences of input data, some important FTire parameters such as radial dynamic stiffness, tangential dynamic stiffness and radial hysteretic stiffness were changed. It can be found from the three models that FTire#c was derived over a wider range of operating conditions, which covers the road obstacles with a height up to 40 mm. FTire#a and FTire#b were derived under the same operating conditions, and this is also used to assess the accuracy of FTire model derived using FE methods. Using different input data including the cornering responses and transient dynamic responses, some FTire parameters such as belt in-plane bending stiffness, radial torsion stiffness and belt twist stiffness and damping should be changed when the model are generated. Particularly, the FTire tools FTire/estim was used to estimates FTire data by comparing its dimensions with a well-known reference tire, and some basic geometry parameters like tread depth and rolling circumference can be estimated. Another tool named FTire/fit was used to identify most of the FTire parameters (cornering stiffness, belt bending stiffness, radial dynamic stiffness, radial hysteresis stiffness etc.) on basis of static and steady-state measurements (or FE prediction results) as well as tire dynamic responses when rolling over cleats. For detailed information, people may refer to reference [33].

4. Multi-body dynamic analysis for tire rolling analysis

A simple tire/wheel model was built in SIMPACK, a commercial multi-body dynamic software. This model is composed of a tire, an axle, and a rim, as shown in Figure 8. Figure 9 shows the topology structure of the tire/wheel model, in which the axle is allowed to travel at a constant velocity in the longitudinal direction, and the rim can only rotate relative to the axle. It is also noted that all the freedoms of the tire relative to the rim are fixed.

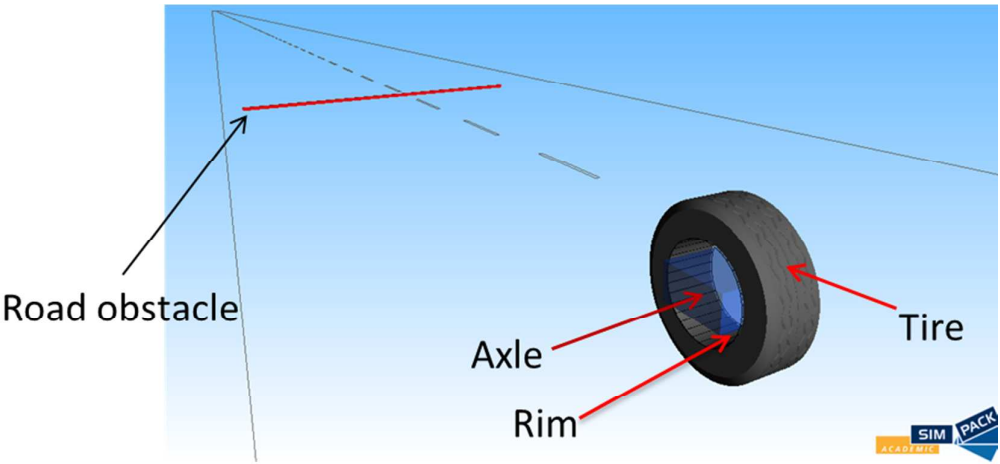


Figure 8 3D tire/wheel model in SIMPACK

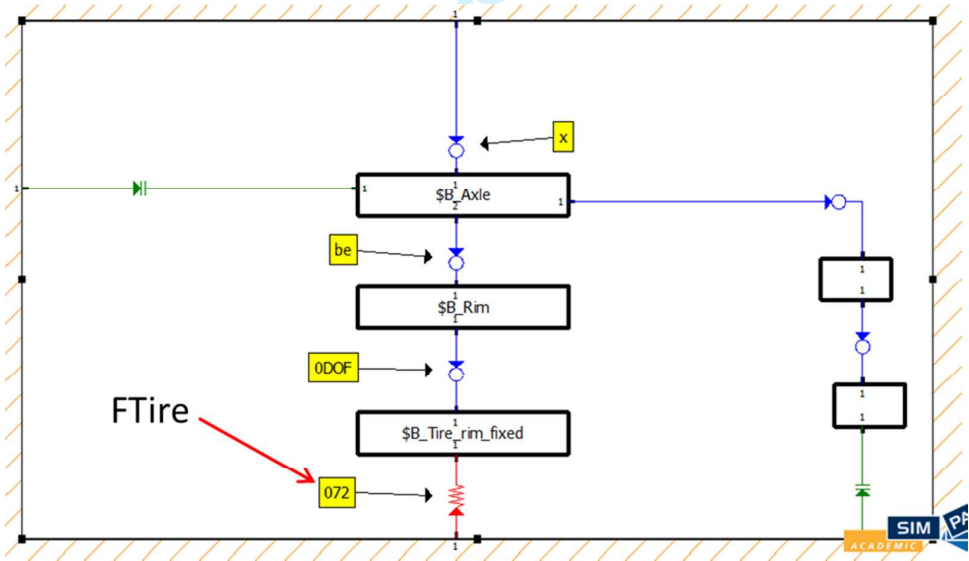


Figure 9. Topology Structure of the tire/wheel model

4.1 Multi-body simulation for tire rolling over obstacles (lower than 25mm)

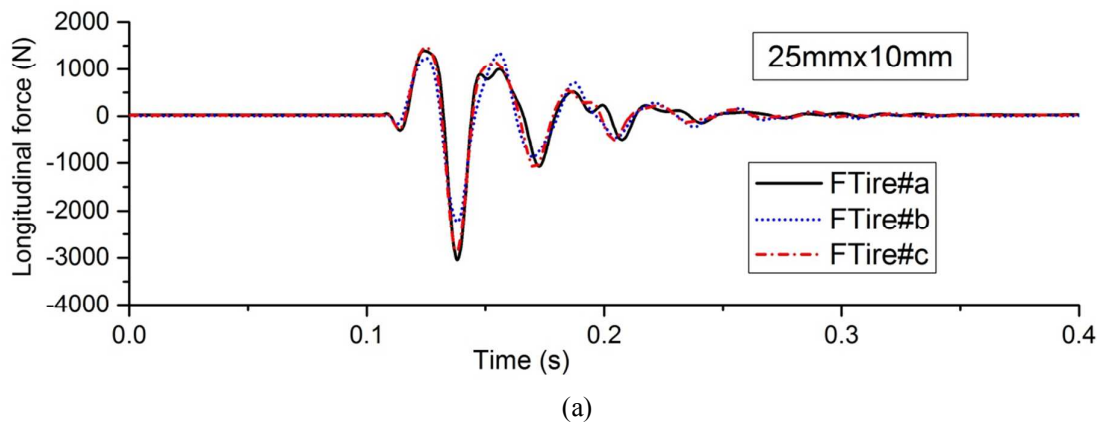
These three different FTire models (FTire#a, FTire#b, FTire#c) were simulated using the multi-body dynamic system for tire rolling analysis, and two different cleats (25 mm ×10 mm, 25 mm × 20 mm) were created for modelling of road obstacles using FTire/road file. As mentioned above, FTire#a was derived using measurement data, in which only obstacles not higher than 25 mm were adopted. Hence, multi-body dynamic simulations are firstly carried out under an available physical test condition in order

that the accuracy of the three FTire models can be examined. It is worthy to note that the available condition means that physical tests can be conducted in this condition. Meanwhile, comparisons between these three FTire models were carried out. The difference between FTire#b and FTire#c is that FTire#c was derived using more simulation data, which means it can cover road conditions with higher obstacles. In this study, the road condition defined by road obstacles lower than 25mm is considered as non-extended condition, while the road condition defined by road obstacles higher than 25mm is considered as extended condition.

Figure 10 shows tire dynamic responses when the tire rolls over 25 mm \times 10 mm obstacle at 30 km/h in SIMPACK. Figure 10(a) describes the longitudinal spindle force variation, and the process is recorded from when the tire starts rolling until the tire traverses the obstacle. Tire longitudinal dynamic responses simulated using the three different FTire models agree well with each other. However, the peak value of longitudinal forces obtained for FTire#b is smaller than for the other two models. This confirms that the FTire model derived from FE model under-predicts the peak longitudinal force as shown in Fig 6. With regard to the tire rolling over 25 mm \times 20 mm obstacle, there is a similar trend with the peak force induced using FTire#b being lower than for the other two models while the dominant frequency of the force induced by FTire#a is slightly higher than for FTire#b and FTire#c. Despite FTire#c model being derived from tire dynamic responses with a wider range of road obstacles, the FTire/fit system is able to tune the model to produce results which are close to the results predicted using FTire#a.

Figure 10(b) and Figure 11(b) show the vertical force variation for tire traversing 25 mm \times 10 mm and 25 mm \times 20 mm obstacles. It can be seen that the vertical dynamic responses predicted using the three different FTire models agree well with each other, particularly for the peak value of the vertical forces. However the dominant frequency with FTire#a is lower than for the other two models. With the comparison between the transient dynamic responses using the three FTire models, the following findings can be deduced:

- FTire models (e.g. FTire#b) derived using the dynamic responses obtained by FE simulations at non-extended condition is capable of predicting tire dynamic responses at non-extended conditions using Multi-body dynamic simulations.
- There are slight differences between transient dynamic responses predicted using FTire#c and FTire#b. Therefore, the FTire model (i.e. FTire#c) derived using the dynamic responses over the wider range of conditions obtained by FE simulations is quite capable of predicting tire dynamic responses at non-extended conditions through Multi-body dynamic simulations.



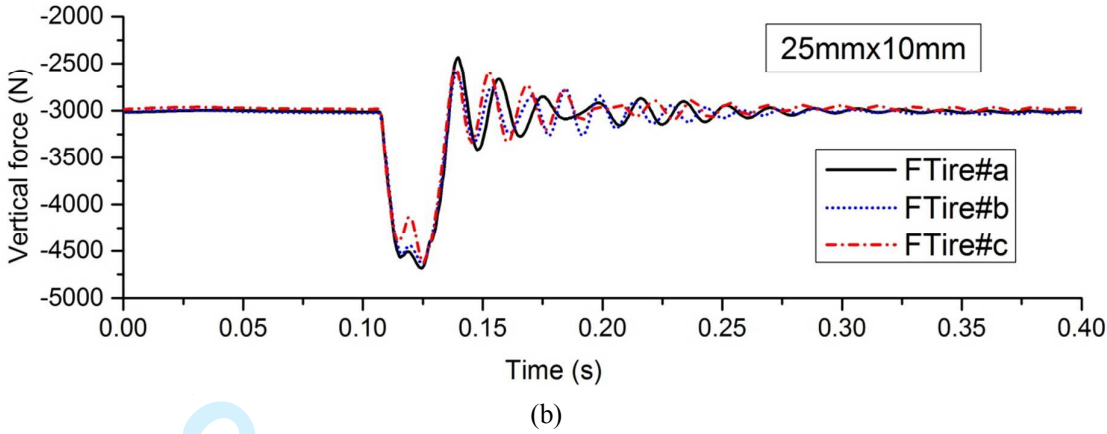


Figure 10. Tire transient dynamic responses for tire traversing 25 mm \times 10 mm cleat. (a) Longitudinal force, (b) Vertical force.

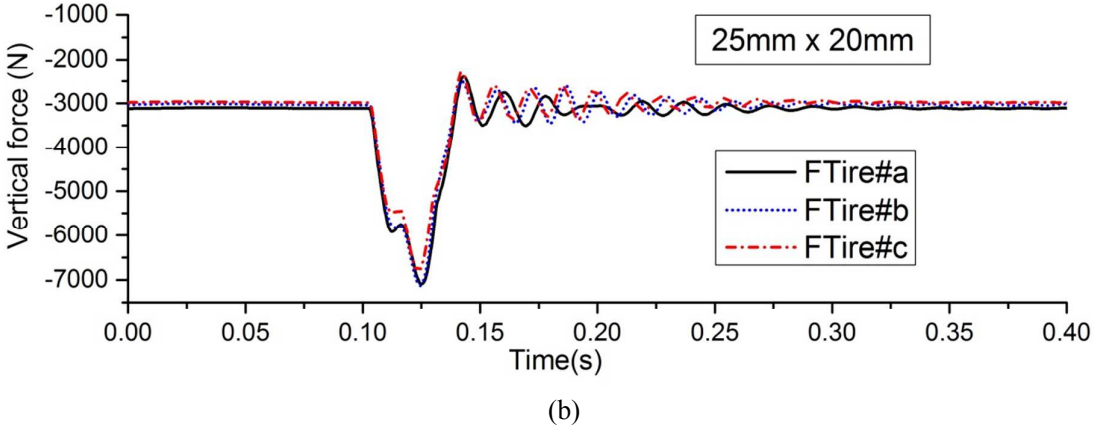
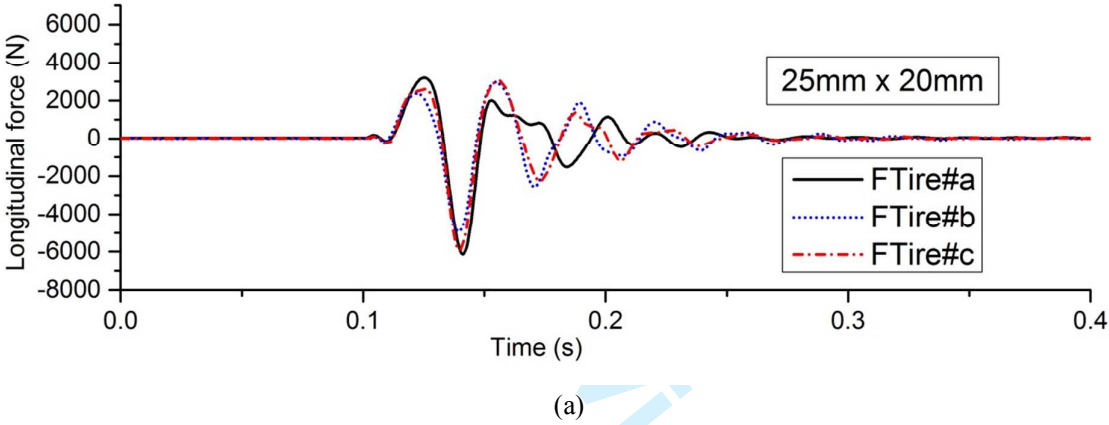


Figure 11. Tire transient dynamic responses for tire traversing 25 mm \times 20 mm cleat. (a) Longitudinal force, (b) Vertical force.

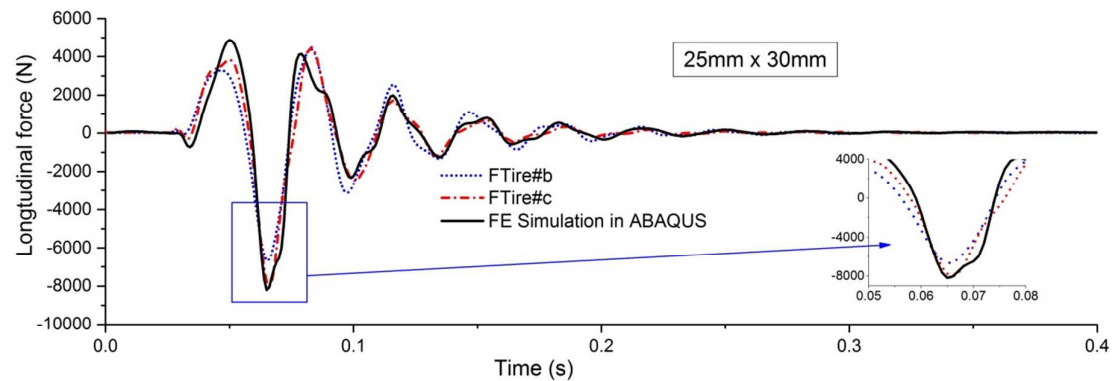
4.2 Multi-body simulation for tire rolling over higher obstacles (higher than 25mm)

In order to investigate the influence of different FTire models on multibody dynamic responses at severe conditions, the two kinds of FTire models (FTire#b, FTire#c) together with the original FE simulation results were considered to make comparisons. FTire#b model was derived by limited FE simulation data, which means the transient dynamic responses did not include the simulation data at extended conditions (cleat higher than 25mm). FTire#c, however, was derived using full simulation data which covered both

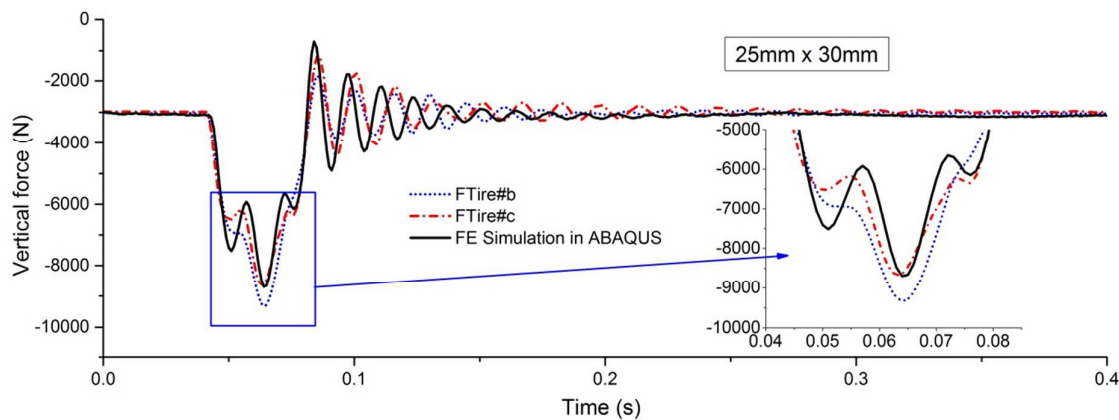
normal conditions (smaller obstacles lower than 25 mm) and extended conditions (obstacle higher than 25 mm). They are compared with the FE simulation results to assess the accuracy of the two FTire models.

In terms of tire rolling over 25mm×30mm obstacle, it can be seen in Figure 12 (a) that the longitudinal responses predicted using FTire#c agrees well with that predicted using FE code ABAQUS. The peak value of the longitudinal forces predicted using FTire#b is smaller than that predicted using the other two methods. On the other hand, Figure 12 (b) shows the vertical responses predicted by FE codes and Multi-body Simulation (MBS) using FTire#b and FTire#c. The general variations of vertical responses for the three cases are similar. However, the peak value predicted using FTire#b is much bigger than that predicted using the other two methods (FE simulation and MBS with FTire#c).

For tire rolling over 25 mm × 40 mm obstacle, the longitudinal dynamic forces predicted using FTire#b and FTire#c have similar characteristics with that predicted using pure FE method (Figure 13). However, the peak value of longitudinal forces obtained by MBS using FTire#c model is closer to the FE simulation result when compared with that obtained by simulation using FTire#b model. The vertical dynamic forces generated when the tire rolls over 25 mm × 40 mm obstacle are shown in Figure 13 (b). The peak value of the vertical forces obtained using FTire#b is much higher than the value obtained for the other two cases, which means inaccurate responses were obtained using the derived FTire#b model.



(a)



(b)

Figure 12. Tire transient dynamic responses for tire traversing 25 mm × 30 mm cleat. (a) Longitudinal force, (b) Vertical force.

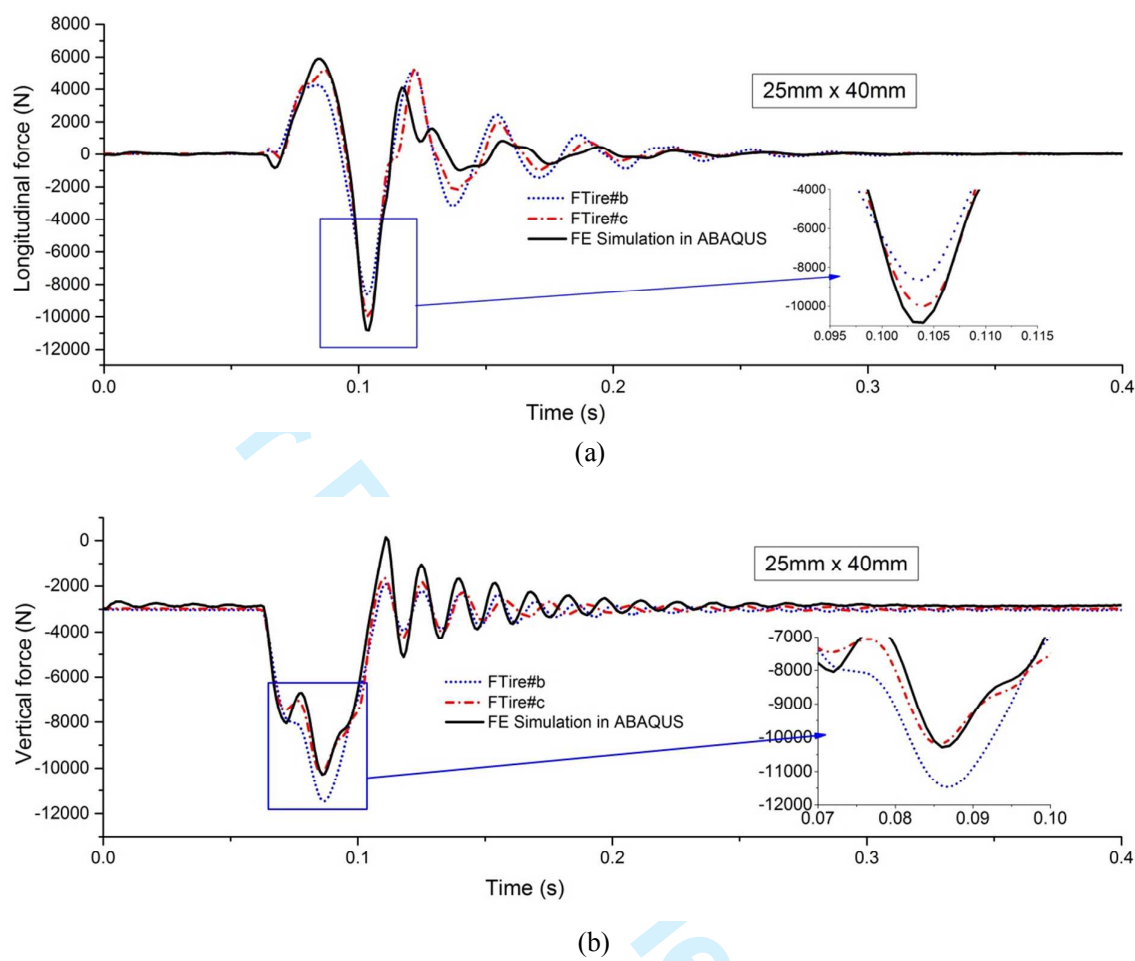


Figure 13. Tire transient dynamic responses for tire traversing 25 mm × 40 mm cleat. (a) Longitudinal force, (b) Vertical force.

Figure 14 shows the predicted tire transient dynamic responses in frequency domain for 30 mm high obstacle. For the longitudinal dynamic forces, the resonant frequencies predicted using the three different tire models are very close to each other. Also, the peak amplitudes in the longitudinal direction for the models have quite small difference. For the vertical dynamic forces, the resonant frequencies for FTire#b, FTire#c and the FE model are 66.5 Hz, 62.8 Hz and 72.3 Hz. These differences are due to the higher dynamic stiffness of the FE tire model.

Figure 15 shows the tire transient dynamic responses for the 40 mm high obstacle in frequency domain. The resonant frequencies for the longitudinal forces are very similar for the three tire models. However, the peak amplitude for them are slightly different with each other, this may be affected by the different longitudinal dynamic stiffness values when impacting large obstacles. For the vertical dynamic forces in frequency domain, the resonant frequency predicted using the FE tire model is higher than that using FTire#b and FTire#c. This difference can be explained by the difference of the dynamic stiffness when impacting large obstacles. Normally, when the tire rolling over large obstacles, the tire will have large deformation, which may lead to the variation of the stiffness due to the nonlinear property of the tire stiffness when large deflection happens.

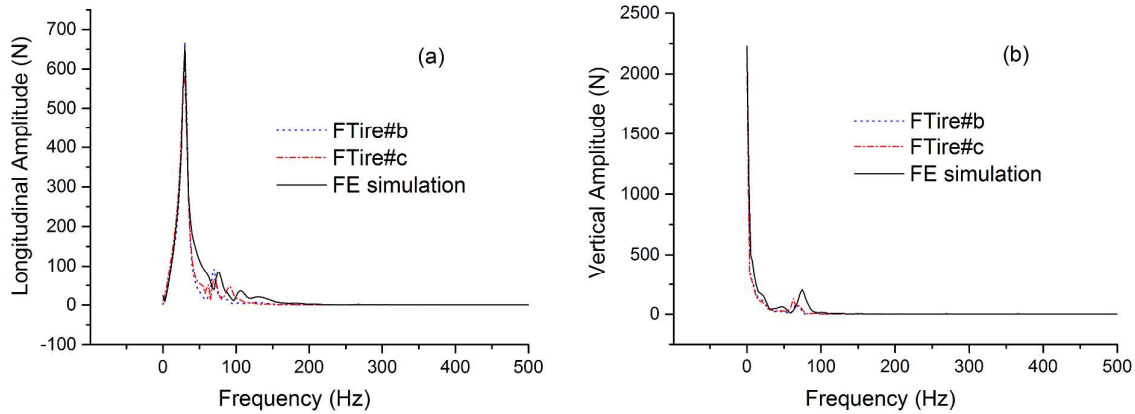


Figure 14 Transient dynamic responses in frequency domain for tire traversing 25 mm \times 30 mm cleat. (a) Longitudinal force, (b) Vertical force

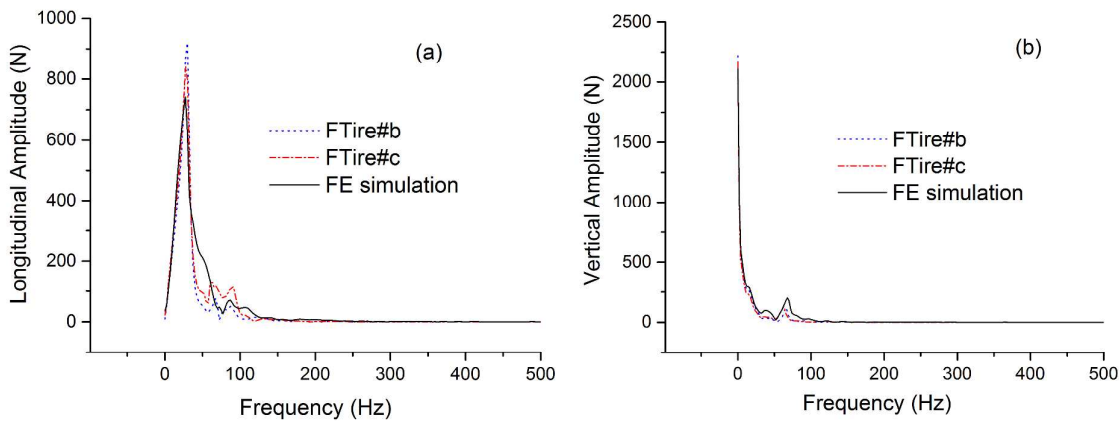


Figure 15 Transient dynamic responses in frequency domain for tire traversing 25 mm \times 40 mm cleat. (a) Longitudinal force, (b) Vertical force

5. Conclusion

A FE tire model has been developed for characterisation of tire behaviour, and the static, steady-state, and transient dynamic behaviour of the tire were used for derivation of FTire parameters. The static stiffness and footprint, cornering stiffness, and transient dynamic responses at non-extended conditions have been predicted and satisfactory validation results were obtained through corresponding measurements.

The FTire parameter derivation was carried out using FTire/fit. The static and steady-state properties, together with transient dynamic property data were used to derive FTire parameters. Three kinds of FTire models were generated based on the experimental data and numerical simulation data.

Multi-body dynamic software SIMPACK was adopted to build a tire/wheel model, the boundary condition of which was set the same as that in numerical simulations. The three different FTire models FTire#a, FTire#b and FTire#c were imported into multi-body dynamic model through an interface.

By comparing the transient dynamic responses obtained from the FTire models under non-extended conditions and extended conditions, the following conclusions can be obtained:

- Both FTire#b and FTire#c are able to be used for predicting tire dynamic responses for tire rolling over obstacles lower than 25mm in SIMPACK. Particularly, the peak value of transient dynamic forces has slight difference between FTire#a, FTire#b and FTire#c.
- With regard to multi-body simulations under extended conditions, FTire#b does not agree well with the FE results in terms of the transient dynamic responses, particularly for the tire impacting on obstacles. Nevertheless, with respect to the peak values of longitudinal forces and vertical forces, the transient dynamic responses obtained using FTire#c showed very satisfactory results in comparison with FE simulation data.
- Multi-body dynamic tire/wheel model associated with FTire model is more efficient to predict transient dynamic properties of rolling tires. The satisfactory results obtained using appropriate FTire model within SIMPACK agree well with results obtained from FE analysis.
- The FTire model tuned using FE simulation including both non-extended and extended conditions can be used for simulation of tire impacting on large obstacles. It also gives more confidence for multi-body dynamic researchers to conduct tire impacting road unevenness simulations using quarter-vehicle and whole vehicle simulations under severe conditions.

References

1. Guan, D.H. and C.J. Fan, *Tire modeling for vertical properties including enveloping properties using experimental modal parameters*. Vehicle System Dynamics, 2003. **40**(6): p. 419-433.
2. Guan, D.H., C.J. Fan, and X.H. Xie, *A dynamic tyre model of vertical performance rolling over cleats*. Vehicle System Dynamics, 2005. **43**: p. 209-222.
3. Besselink, I.J.M., A.J.C. Schmeitz, and H.B. Pacejka, *An improved Magic Formula/Swift tyre model that can handle inflation pressure changes*. Vehicle System Dynamics, 2010. **48**: p. 337-352.
4. Balaramakrishna, N. and R.K. Kumar, *A study on the estimation of SWIFT model parameters by finite element analysis*. Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering, 2009. **223**(D10): p. 1283-1300.
5. Gipser, M., *The FTire Tire Model Family*. Automotive Engineering, 1998.
6. Gipser, M., *FTire, a New Fast Tire Model for Ride Comfort Simulations*, in *International ADAMS User's conference 1999*: Berlin.
7. Gipser, M., *FTire: a physically based application-oriented tyre model for use with detailed MBS and finite-element suspension models*. Vehicle System Dynamics, 2005. **43**: p. 76-91.
8. Gipser, M., *FTire - the tire simulation model for all applications related to vehicle dynamics*. Vehicle System Dynamics, 2007. **45**: p. 139-151.
9. Gipser, M., *FTire: 10 Years of Development and Application*. www.cosin.eu, 2008.
10. Gipser M., H.R., Lugner P., *Dynamical Tyre Forces Response to Road Unevennesses*. Vehicle System Dynamics Supplement, 1997. **27**.
11. Riepl, A., W. Reinalter, and M. Schmid, *Application of the tyre model FTire in the vehicle development process at MAGNA STEYR Fahrzeugtechnik*. Vehicle System Dynamics, 2005. **43**: p. 370-383.
12. Riepl, A., W. Reinalter, and G. Fruhmann, *Rough road simulation with tire model RMOD-K and FTire*. Dynamics of Vehicles on Roads and on Tracks, 2003: p. 734-743.
13. Haga, H., *Evaluation of tyre models for durability loads prediction using a suspension-on-a-drum environment*. Vehicle System Dynamics, 2005. **43**: p. 281-296.

14. Dorfi, H.R., *Tire Cleat Impact and Force Transmission: Modeling Based on FTIRE and Correlation to Experimental Data*. 2004, SAE International.
15. Dorfi, H.R., *A Study of the In-Plane Force Transmission of Tires*. Tire Science and Technology, 2004. **32**(4): p. 188-213.
16. Olatunbosun, O.A. and A.M. Burke, *Finite Element Modelling of Rotating Tires in the Time Domain*. Tire Science and Technology, 2002. **30**(1): p. 19-33.
17. Kao, B.G. and M. Muthukrishnan, *Tire Transient Analysis with an Explicit Finite Element Program*. Tire Science and Technology, 1997. **25**(4): p. 230-244.
18. Kamoulakos, A. and B.G. Kao, *Transient Dynamics of a Tire Rolling over Small Obstacles — A Finite Element Approach with PAM-SHOCK*. Tire Science and Technology, 1998. **26**(2): p. 84-108.
19. Cho, J.R., K.W. Kim, D.H. Jeon, and W.S. Yoo, *Transient dynamic response analysis of 3-D patterned tire rolling over cleat*. European Journal of Mechanics - A/Solids, 2005. **24**(3): p. 519-531.
20. Wei, C. and O.A. Olatunbosun, *Transient dynamic behaviour of finite element tire traversing obstacles with different heights*. Journal of Terramechanics, 2014. **56**(0): p. 1-16.
21. Wei, C. and O.A. Olatunbosun, *The effects of tyre material and structure properties on relaxation length using finite element method*. Materials & Design, 2016. **102**: p. 14-20.
22. Yeoh, O.H. and P.D. Fleming, *A new attempt to reconcile the statistical and phenomenological theories of rubber elasticity*. Journal of Polymer Science Part B-Polymer Physics, 1997. **35**(12): p. 1919-1931.
23. *ABAQUS™/CAE User's Manual*. Dassault Systemes. ABAQUS™ Ver. 6.12.
24. Yang, X., *Finite element analysis and experimental investigation of tyre characteristics for developing strain-based intelligent tyre system*, in *Mechanical Engineering*. 2009, University of Birmingham: Birmingham.
25. Burke, A.M. and O.A. Olatunbosun, *Contact modelling of the tyre/road interface*. International Journal of Vehicle Design, 1997. **18**(2): p. 194-202.
26. Elwaleed, A.K., A. Yahya, M. Zohadie, D. Ahmad, and A.F. Kheiralla, *Effect of inflation pressure on motion resistance ratio of a high-lug agricultural tyre*. Journal of Terramechanics, 2006. **43**(2): p. 69-84.
27. Lyasko, M.I., *The Determination of Deflection and Contact Characteristics of a Pneumatic Tire on a Rigid Surface*. Journal of Terramechanics, 1994. **31**(4): p. 239-246.
28. Mohsenimanesh, A. and S.M. Ward, *Estimation of a three-dimensional tyre footprint using dynamic soil-tyre contact pressures*. Journal of Terramechanics, 2010. **47**(6): p. 415-421.
29. XU Zhe, W.W., ZHAO Shu-gao, *FEA on static and cornering stiffness characteristics of radial tire*. China Rubber Industry, 2010.
30. Korunović, N., M. Trajanović, and M. Stojković, *Finite element model for steady-state rolling tire analysis*. Journal of the Serbian Society for Computational Mechanics/Vol, 2007. **1**(1): p. 63-79.
31. Koishi, M., K. Kabe, and M. Shiratori, *Tire Cornering Simulation Using an Explicit Finite Element Analysis Code*. Tire Science and Technology, 1998. **26**(2): p. 109-119.
32. Olatunbosun, O.A. and O. Bolarinwa, *FE Simulation of the Effect of Tire Design Parameters on Lateral Forces and Moments*. Tire Science and Technology, 2004. **32**(3): p. 146-163.
33. Michael Gipser, G.H., *FTire Parameterization*. <https://www.cosin.eu/>